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Localization of X-ray Sources in Six Galactic Globular Clusters from Chandra Data

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Abstract—We present our observations of six Galactic globular clusters where the following bright X-ray sources were observed: NGC 6440, NGC 6441, NGC 6624, Terzan 1, Terzan 2, and Terzan 6. Using the Chandra observatory, we were able to achieve a localization accuracy of $0''.6$ for X-ray sources in the globular clusters. The error circle considerably decreased compared to the observations of other observatories, by more than a factor of 10 for some clusters. We detected at least one X-ray source in each of the globular clusters studied and 12 sources in the globular cluster NGC 6440. The source XB1733-30 in Terzan 1 was not detected by the Chandra observatory; we obtained an upper limit on its luminosity.

Key words: *X-ray and gamma-ray sources*

INTRODUCTION

Galactic globular clusters have always been among the objects of particular interest for X-ray astronomy (Hut *et al.* 1992). Estimates show that the globular clusters contain much more X-ray binaries per unit mass than the rest of the Galaxy (Clark 1975).

Initially, it was hypothesized that the X-ray sources in globular clusters could be massive black holes (Bahcall and Ostriker 1975) or black holes of stellar mass (Grindlay 1978). However, the bright X-ray objects in globular clusters were subsequently found to be the sources of type-I X-ray bursts. Thus, presently, these X-ray sources are generally recognized to be binaries with neutron stars. However, new observations show that many globular clusters also contain a considerable number of weaker X-ray sources (Grindlay *et al.* 2001). In this case, it is not clear whether all these sources are X-ray bursters or a heterogeneous set of objects.

Six of the twelve known bright X-ray sources in globular clusters were localized most accurately (with an accuracy of $\sim 2''-3''$) using the HRI instrument onboard the EINSTEIN observatory. This allowed the masses of these binaries to be estimated from the radial distances of the sources from the globular-cluster centers (Grindlay *et al.* 1984). The measured radial distances of the bursters from the globular-cluster centers agree with the assumed binary masses of $\sim 2M_{\odot}$.

The Chandra new-generation X-ray observatory with an angular resolution of $0'.5$ has allowed the localizations of known X-ray sources to be significantly improved. This, in turn, makes it possible to identify these objects more reliably in the optical and radio ranges (see, e.g., Heindl and Smith 2001; Revnivtsev and Sunyaev 2002). In particular, substantial progress has been made in localizing X-ray sources in globular clusters (Grindlay *et al.* 2001; Heinke *et al.* 2001; Homer *et al.* 2001).

Here, we present our localization results and estimates of the X-ray fluxes for sources in six Galactic globular clusters from Chandra observations.

OBSERVATIONS AND RESULTS

For our analysis, we used the following publicly available data from the Chandra X-ray observatory: NGC 6440—July 4, 2000 (the ACIS-S focal detector, an exposure time of ~23 ks); NGC 6441—May 23, 2000 (HRC-I, ~2.3 ks); NGC 6624—October 3, 2000 (HRC-S, ~15 ks); NGC 6652—May 23, 2000 (HRC-I, ~1.7 ks); Terzan 1—March 9, 2000 (HRC-I, ~3.6 ks); Terzan 2—March 9, 2000 (HRC-S, ~10 ks); and Terzan 6—March 9, 2000 (HRC-I, ~10 ks). The data were reduced with the CIAO v2.1.2 standard software package.

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The positions of X-ray sources in globular clusters and some globular-cluster parameters

ID	Position of globular cluster center		Nucleus radius	$R_{1/2}$	D, kpc	Position of X-ray source		Distance from center	Luminosity, $\log(L$, erg s^{-1})
	$\alpha(2000)$	$\delta(2000)$				$\alpha(2000)$	$\delta(2000)$		
NGC 6440	$17^h48^m52\overset{s}{.}6$	$-20°21'34''$	$7''.8$	$34''.8$	6.4	$17^h48^m55\overset{s}{.}02$	$-20°21'33''.8$	$34''.03$	31.2
–	–	–	–	–	–	17 48 53.32	−20 21 41.7	12.72	32.1
–	–	–	–	–	–	17 48 53.17	−20 21 38.7	9.23	32.2
–	–	–	–	–	–	17 48 53.12	−20 21 27.0	10.1	31.2
–	–	–	–	–	–	17 48 52.93	−20 21 39.1	6.89	31.6
–	–	–	–	–		17 48 52.87	−20 21 42.5	9.31	32.0
–	–	–	–	–	–	17 48 52.85	−20 21 34.1	3.51	32.0
–	–	–	–	–	–	17 48 52.64	−20 21 40.6	6.62	31.6
–	–	–	–	–	–	17 48 52.41	−20 21 32.2	3.22	32.3
–	–	–	–	–	–	17 48 52.16	−20 21.32.4	6.39	32.5
–	–	–	–	–	–	17 48 51.98	−20 21 46.7	15.40	31.7
–	–	–	–	–	–	17 48 51.87	−20 21 33.9	10.27	31.0
NGC 6441	17 50 12.9	−37 03 04	6.6	38.4	11.2	17 50 12.74	−37 03 06.8	3.39	36.6
NGC 6624	18 23 40.5	−30 21 40	3.6	49.2	8.0	18 23 40.46	−30 21 40.3	0.60	37.2
Terzan 1	17 35 46.8	−30 28 52.7	2.4	229.2	6.2	17 35 45.61	−30 29 00.2	30.2	32.4
Terzan 2	17 27 33.4	−30 48 08	1.8	91.2	8.7	17 27 33.15	−30 48 07.8	3.23	36.8
Terzan 6	17 50 46.4	−31 16 31	3.0	26.4	9.5	17 50 46.90	−31 16 29.5	6.58	35.2

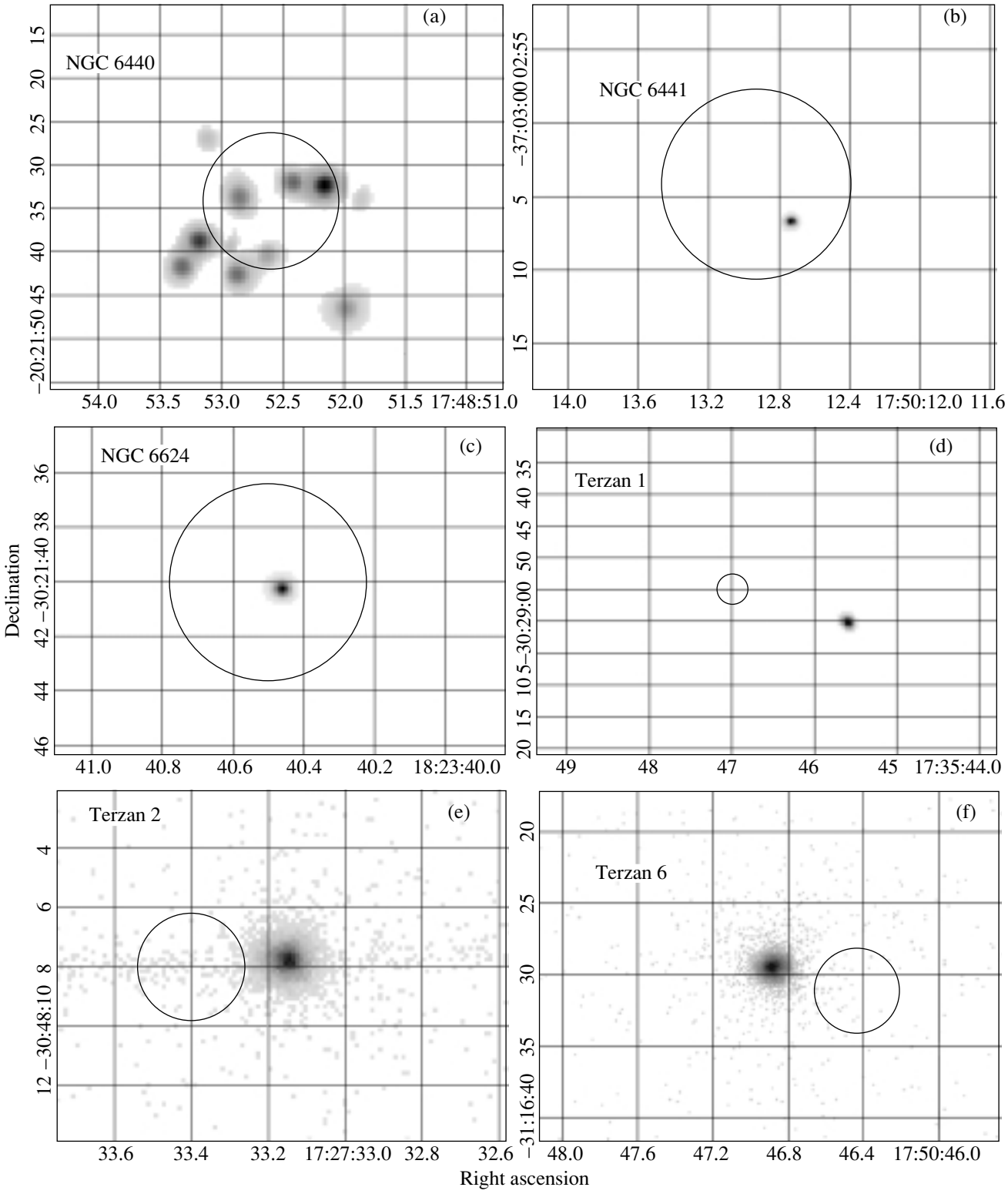
We also used observational data for the globular clusters NGC 6652 and NGC 1851. Since the results of our analysis agree, within the error limits, with the localizations published by Heinke *et al.* (2001) and Homer *et al.* (2001), we do not present the results of our analysis for these observations here and refer the interested reader to the corresponding papers.

The Chandra design localization accuracy is $\sim 1'$. However, an analysis of simultaneous optical and X-ray observations of various sky fields shows that the Chandra ($1\text{-}\sigma$) localization accuracy of X-ray sources is $\sim 0''.6$ (see http://asc.harvard.edu/mta/ASPECT/cel_loc/cel_loc.html and http://asc.harvard.edu/mta/ASPECT/celmon/).

To detect and locate the sources, we used the *wavdetect* procedure of the CIAO2.0 package. In this procedure, the source confidence level is determined by estimating the observed background fluctuations. Since all the sources under study are close to the center of the field of view, their images are compact and the statistical uncertainty in the source position is negligible compared to the previously mentioned systematic uncertainty.

Our observations of all six globular clusters revealed at least one X-ray source with a detection confidence level above 4σ within the radius $R_{1/2}$ containing half of the cluster mass. Twelve sources were detected in the globular cluster NGC 6440 within $R_{1/2}$. Note that the only source found in the globular cluster Terzan 1 does not coincide in position with the previously observed bright X-ray burster MX1733-30. Thus, the Chandra observations put an upper limit on the flux from MX1733-30, $L_x \lesssim 4 \times 10^{32}$ erg s^{-1}. It should be borne in mind, however, that if the burster XB1733-30 in its off state has a very soft spectrum (with an effective temperature of $kT \sim 0.1$–0.2 keV; see Campana *et al.* 2000), much of the soft X-ray radiation with $h\nu \lesssim 1$–2 keV can be absorbed on the line of sight.

Since the HRC detector with a very low spectral resolution was used in all our observations except those of NGC 6440, a spectral analysis of the detected sources cannot be performed. To transform the instrumental counts to the energy fluxes from the sources, we used an arbitrary spectral model, a bremsstrahlung model with the temperature $kT =$ 2 keV (the energy range 0.5–7.0 keV). Thus, it should be remembered that our luminosity estimates for the X-ray sources have a systematic uncertainty that stems from the fact that the actual shapes of their



Chandra (0.5–7 keV) images of the globular clusters. The circle indicates the location and size of the globular-cluster nucleus.

spectra are unknown. We plan to perform a spectral analysis of the sources in NGC 6440 in a separate paper.

The table contains the positions of the detected bright X-ray sources. It also gives some parameters of the globular clusters (positions of their centers; nucleus radii; and distances to the clusters). The parameters of the globular clusters except for Terzan 1 were taken from the catalog by Harris (1996). For the cluster Terzan 1, we used data from the catalog by Webbink (1985).[1] The figure shows the Chandra X-ray images of the globular clusters. The circles in the panels indicate the locations and sizes of the globular-cluster nuclei.

Note that according to the Chandra observations, the X-ray source in the globular cluster NGC 6441 is at a distance of $\sim 1\farcs6$ from the position of star U1, which was suggested as an optical counterpart of this source (Deutsch *et al.* 1998). Such a large separation between the positions of the X-ray source and its presumed counterpart calls into question the optical identification of the X-ray source. The localization of the X-ray source in the globular cluster NGC 6441 given in the Table suggests that it lies closer to the cluster center than assumed previously. The new position does not rule out its identification with one of the blue stars that are also described in Deutsch *et al.* (1998).

CONSLUSIONS

We have presented the results of our analysis of the Chandra observations for six Galactic globular clusters. At least one X-ray source was detected in each globular cluster within the radius containing half of the cluster mass. Twelve X-ray sources were detected in the globular cluster NGC 6440; one of them coincides in position with the previously observed source MX1746–20 (Johnston *et al.* 1995). The only source found in Terzan 1 does not coincide in position with the previously observed burster XB1733-30 (Pavlinsky *et al.* 2001; Johnston *et al.* 1995). The localization accuracy of the X-ray sources in Terzan 2, NGC 6624, Terzan 6, and NGC 6440 has improved by a factor of 3 to 10 compared to the ROSAT and EINSTEIN results.

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[1] The coordinates of the center of the globular cluster Terzan 1 in Harris (1996) significantly differ from those in other catalogs. The table gives the coordinates from Webbink (1985).